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Spectropolarimetry of Young and Evolved Stars

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Abstract. Circumstellar disks play an important role in many stages of the evolution of stars. However, it is only possible to directly image circumstellar disks for a few of the nearest stars. For massive stars, the situation is even more difficult, as they are on average further away than the more numerous low mass stars. In order to shed light on such disks we are pursuing a programme of spectropolarimetry. This technique can reveal the presence of disks on a spatial scale of order stellar radii, while it has the potential for further modeling. Here we present our results on two groups of stars, on young, intermediate mass, pre-main sequence Herbig Ae/Be stars and on a sample of massive evolved objects, the Luminous Blue Variables. We also present initial results obtained at near-infrared wavelengths.

1. Spectropolarimetry as a Technique

The principle of the method is rather simple: it exploits the fact that the free electrons in an extended, ionized disk scatter the continuum radiation from the central star more efficiently than the emission from hydrogen recombination lines which are formed within the disk itself. Due to the electron scattering, the emerging light will be linearly polarized, but the photospheric light will be more polarized than that of the emission line, as the latter travels a shorter distance through the disk.

Therefore, a change in the polarization spectrum across an emission line such as Hα indicates the presence of a flattened structure. In the case of a non-detection, the situation is less clear-cut. It could either be that the disk is face-on in the line of sight, or that the star is not surrounded by a disk at all, but by some spherically symmetric structure instead. In these cases all polarization vectors cancel, giving zero polarization in both line and continuum.

A low spectral resolution version of this technique was already explored in the seventies by Poeckert & Marlborough (1976), who used narrow-band polarimetry to prove that Be stars are surrounded by ionized disks. This result could be directly confirmed only many years later by high spatial resolution radio and optical interferometry (Dougherty & Taylor 1992, and Quirrenbach et al 1997, respectively). As electron scattering occurs at scales of a few stellar radii (Cassinelli et al. 1987), the method provides a means to detect disks that otherwise can not be found. With the advent of CCD detectors and the installation of stable and efficient polarization optics, it has become possible to make routine spectropolarimetric observations at medium to high resolution.

2. Pre-Main Sequence Stars

We have applied the technique to the intermediate mass pre-main sequence Herbig Ae/Be stars with the primary goal of investigating whether these objects accrete material via a disk or not. The very presence of massive stars still poses a mystery; the radiation pressure from a newly born, yet still accreting star, may blow away the infalling material, halting further growth (e.g. Yorke & Kruegel 1977). However, a disk can withstand the radiation pressure much better (Yorke & Sonnhalter 2002), and may be able to supply the necessary material to allow the star to reach higher masses. To within our sensitivity, more than half of the two dozen objects surveyed show a line effect. As the systems are oriented randomly in the line of sight, it is not unexpected that some targets, even if surrounded by a disk, would not show a line effect in our data. In fact, the detection rate does indicate the presence of a disk, and implies that all systems are indeed surrounded by disks. Our survey therefore provides evidence that disk accretion is in contention to explain the formation of massive stars (Oudmaijer & Drew 1999; Vink et al 2002).

For a large fraction of the stars, more than just a simple depolarization signature is seen, and instances of enhanced polarization are observed. This occurs more often in the cooler Herbig Ae stars than in the Herbig Be stars. It can be explained by the presence of hot spots on the stellar surface - resulting in enhanced Hα line polarization compared to the stellar photosphere as a whole (e.g. Pontefract et al 2000). An added bonus is that we observed similar effects in the lower mass T Tau stars (Vink et al 2003, see also Vink in these proceedings). The similarity in the spectropolarimetric behaviour of the convective T Tauri stars and their hotter Herbig Ae counterparts strongly suggests that magnetically controlled accretion plays also a role in these more massive stars.

3. Going Extra-Galactic: Luminous Blue Variables

We are now pushing the technique to its limit by observing extra-galactic objects. Specifically, we have observed a large sample of both Galactic and Magellanic Cloud Luminous Blue Variables (LBV). These stars are thought to be the link between the main sequence O stars and the final products of massive-star evolution. It has been observed that their large scale structures have bipolar morphologies (Nota et al 1995). However, it remains unclear whether these bipolar nebulae are due to spherically symmetric winds interacting with a pre-existing density contrast or whether the star is undergoing enhanced mass loss in the equatorial plane, perhaps due to rotation (Dwarkadas & Balick 1998; Dwarkadas & Owocki 2002). To probe the mass loss geometry of these objects in more detail, and to constrain the role of rotation in massive star evolution, we embarked on a spectropolarimetric survey of these massive evolved stars.

We observed all "confirmed" LBVs in the Galaxy (7) and Magellanic Clouds (6). The stars are listed as confirmed LBVs by Humphreys and Davidson (1994)

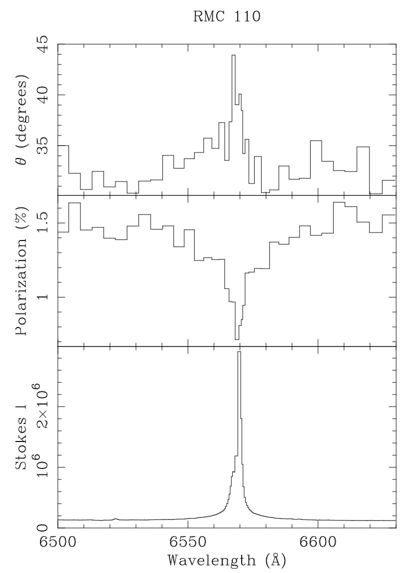

Figure 1. The polarization spectrum across Hα of the Luminous Blue Variable RMC 110 in the Large Magellanic Cloud. The bottom panel shows the intensity spectrum, while the middle and upper panels show the polarization and position angle respectively, rebinned to a corresponding accuracy in the polarization of 0.13% (1σ). Note the de-polarization across the emission line.

and van Genderen (2001), and constitute one of the largest samples of LBVs that have been observed with the same instrumental set-up. We find several instances of depolarization effects in the LBVs, indicating that these massive objects are surrounded by flattened structures very close to the star. An example is shown in Figure 1.

The analysis is in progress. The main result is that roughly half of the objects show a line effect and thus evidence for disks. In comparison Harries et al (1998) find that only 10% of Wolf-Rayet stars show this effect, while the majority of evolved B[e] supergiants do (Schulte-Ladbeck et al 1993; Oudmaijer & Drew 1999). Pending further analysis, the data may hint at different evolutionary sequences for WR stars and LBVs (see Lamers et al 2001, for a review on the evolutionary status of LBVs).

4. Prospects at Longer Wavelengths

The previous sections discussed Hα data and the application of the method to optically visible objects. As we aim to resolve the line-profiles, and the method needs millions of photons to achieve $\sim 0.1\%$ accuracy in polarization, the objects that can be properly studied on 4m class telescopes are limited in brightness to about $V < 10$. There are plans to equip the 8m telescopes' spectrographs, operating at similar spectral resolution, with polarimetric capabilities, moving the limit a few magnitudes fainter.

However, a class of object that remains elusive even in the 8m era are the deeply embedded massive Young Stellar Objects. These objects are the "Herbig Ae/Be" equivalent of the most massive stars, and their formation is even more

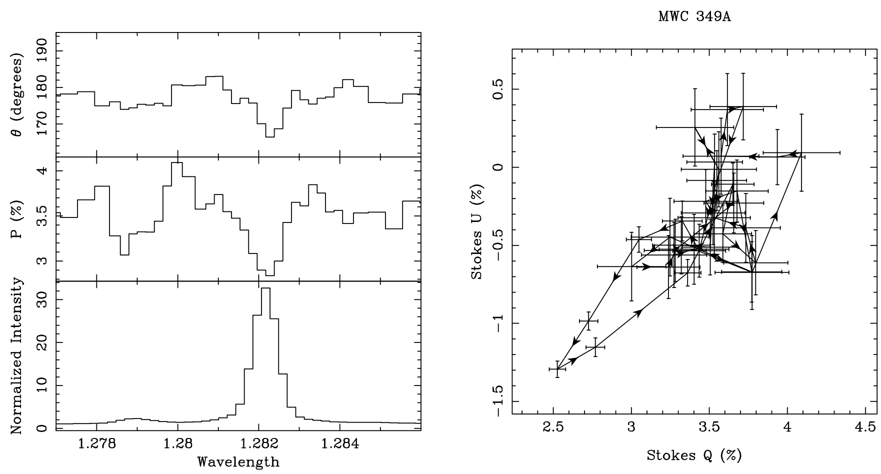

Figure 2. Paβ polarization data of MWC 349A. The left hand graph shows the polarization data, as in Figure 1, now as a function of wavelength in μm. The bottom panel shows the (normalized) intensity spectrum, the data are rebinned to a corresponding accuracy in the polarization of 0.25% The right hand plot shows the Stokes QU vectors with the same binning applied. MWC349A shows an effect across the Paβ emission line, while the, much weaker, He I λ 1.27842 μm line also displays a depolarization.

enshrouded in mystery. This is mainly due to the fact that they are extremely rare and that the Kelvin-Helmholtz contraction timescales are much shorter than the natal cloud's freefall time. They are therefore optically invisible and have most of their light output in the infrared.

To be able to determine whether (accretion) disks around such objects are present we need to go to longer wavelengths where the objects become more visible. Infrared hydrogen recombination lines are fairly strong (Bunn et al 1995) and spectropolarimetry could be a powerful tool to probe their inner regions. Little medium resolution spectropolarimetry has been performed in the near-infrared, and we present here some of the very first data across atomic lines of a stellar object.

We undertook proof-of-concept observations at UKIRT and observed among others the enigmatic object MWC 349A. The results around the Paβ line are shown in Figure 2; the data show a clear depolarization, and are consistent with the optical data presented by Meyer et al (2002). This is a reassuring test, and observations are planned for the embedded Young Stellar Objects.

5. Summary

In this contribution we have presented applications of spectropolarimetry in the optical to pre-main sequence Herbig Ae/Be stars and evolved Luminous Blue Variables. In addition, we have shown our initial near-infrared data on embedded objects. The technique itself is powerful as it is capable of probing to scales of order stellar radii, and shows promise for follow-up modeling as indicated by Vink et al in these proceedings.

The success in applying the method in the near-infrared is a motivation to move on, and the natural next step will be to establish the presence or absence of accretion disks in the most massive pre-main sequence stars to provide insights on how such objects actually form.

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Discussion

J. Bjorkman: Electron scattering in a dense expanding wind produces redshifted broadening of the H alpha emission, which should be polarized for disklike systems. Do you see any evidence for such an asymmetry in your H alpha polarization profiles?

Oudmaijer: Indeed one could expect such an effect, particularly for the evolved stars as they are known to have outflows. We are currently analyzing the data, but no obvious signs have been detected yet. This is most likely the result of the combination of the “coarse” spectral resolution of our data (in velocity space it is typically similar to or larger than a typical outflow velocity) with the relatively low signal-to-noise that one gets in the polarization data - of course, the total spectra from which the polarization is derived have much higher SNR. With our evolved star data we are pushing the instrumentation to its limit.